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Sensor Less Control of Position and Displacements of Bearing Less Switched Reluctance Motor by using Sliding Mode Observer

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Abstract: In this study, a novel indirect sensorless sliding mode observer based displacement and position sensing techniques are proposed for Bearing less Switched Reluctance Motor (BSRM) to avoid the limitations of the mechanical sensors and to get the fast dynamic response for high-speed operations. To get fast convergence and more robustness against parameter variations in view of both mechanical and electrical disturbances, the sliding mode observer design is very appropriate for the BSRM. The conventional on-off hysteresis current controller and asymmetric converters are used for the estimation of position and displacements. Under different initial states, variations of drive parameters and suspension load disturbance conditions the performance of proposed SMO for BSRM was simulated to verify the robustness. At the instant of change of load there is a temporary increment of errors of position and rotor displacements of proposed SMO for BSRM. The whole system reached its expected precision tracking. The fast convergence rate and more robustness and disturbance rejection capability properties are carefully studied. The observer can provide stable and accurate position estimation and displacement estimation and speed estimation even there is an unexpected variations in reference and suspension loading conditions.

Key words: Asymmetric converter, hysteresis controller, rotor displacement, sliding mode observer, BSRM, appropriate

INTRODUCTION

For high-speed applications, the magnetic bearings are integrated into motor's structure to avoid the lubrication and friction between the rotor shafts and bearings is called as bearing less technology. The BSRM realizes both levitation and rotation at the same instant by integrating the magnetic suspension winding into the stator of the motor. A bearing less SRM drive generally needs a rotor displacement sensor and position sensors to control speed, torque and rotor displacements which will add complexity to drive, increases the cost and size of the whole drive system (Zhan *et al*., 1999; McCann *et al*., 2001). And also, causes some practical limitations to get accurate rotor angle measurement and radial displacement measurement values to improve the performance for industrial applications (Islam *et al*., 2003; Davijani *et al*., 2016). Thus, for the purpose of eliminating this physical position sensors and displacement sensors, many indirect position and displacement identifying techniques have been proposed for BSRM drives in current years.

There are two major indirect position methods for Switched Reluctance type Motor (SRM) drives to eliminate physical position sensor. One of them is based on waveform detection method. This method is based on the measurement of inductance deviations in one of the un-energized phases. Another significant method is established from the information that the terminal voltage and currents of an SRM drive. The both phase voltages and currents holds the essential information to re-form the rotor position and its displacement from the center. To overcome the above said problems and estimation of both position sensing and displacement sensing separately an indirect sensor less Sliding Mode Observer (SMO) is designed based on phase voltages and currents. While designing of sliding mode observer, the magnetic saturation, load disturbances, parameter variations (both mechanically and electrically) are considered.

In this study, the speed, position control and displacement control of Bearing less Switched Reluctance Motor (BSRM) with 12 salient poles on the stator and 14 salient poles on the rotor by using sensorless sliding

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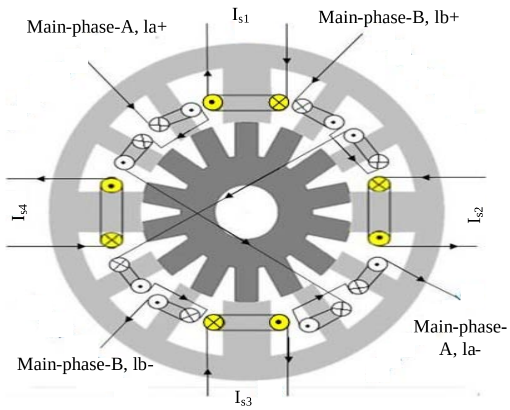

Fig. 1: Winding pattern of BSRM

mode observer are designed. There are two types of windings on the stator and there are no windings on the rotor (Takemoto *et al.*, 2000a, b; Takemoto *et al.*, 2001). To get the decoupling behavior between suspending force and torque, the DC supply is given independently to the suspension coils and torque coils (Lee and Ahn, 2011; Morrison, 2004; Morrison *et al.*, 2008; Lee *et al.*, 2007). The motor dynamics and magnetic bearing rotor dynamics are modeled into state space format. Due to state space, it avoids the generation of negative torques and the need of extra diagnostic circuitry. The drive incorporates two hysteresis control loops for the torque currents and four for the suspension force. The fast convergence rate and robustness and disturbance rejection capability properties are carefully analysed. The 12/14 BSRM winding pattern and its structure are illustrated in Fig. 1.

MATERIALS AND METHODS

Non-linear modeling of the BSRM: The BSRM drive system was modeled with considering of magnetic nonlinear properties of both torque winding and suspension winding. With the use of both voltage and currents, sliding mode observer estimation modeling is done along with lookup tables. The assumption is taken while modeling of motoring system is that each phase is magnetically decoupled. The rotor dynamics of bearing less SRM is written by:

$$F_x = m\frac{d^2x}{dt^2}+kx;\; F_y = m\frac{d^2y}{dt^2}+ky+mg \qquad (1)$$

The net suspending force equations for BSRM is given by:

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \begin{bmatrix} K_{xxp} & K_{xyp} & K_{xxn} & K_{xyn} \\ K_{yxp} & K_{yyp} & K_{yxn} & K_{yyn} \end{bmatrix} \begin{bmatrix} i_{xp}^2 \\ i_{yp}^2 \\ i_{xn}^2 \\ i_{xn}^2 \end{bmatrix} \qquad (2)$$

By combining above two equations, we get:

$$F_x = m\frac{d^2x}{dt^2} = [K_X][I_x] \qquad (3)$$

$$Fy = m\frac{d^2y}{dt^2}+mg = [K_Y][I_Y] \qquad (4)$$

Where:

$$I_x = \begin{bmatrix} I_{xp}^2 \\ I_{xn}^2 \end{bmatrix}$$

$$I_Y = \begin{bmatrix} I_{yp}^2 \\ I_{yn}^2 \end{bmatrix}$$

Where:

$$K_x = \text{diag}\left[K_{xxp}\ K_{xyp}\ K_{xxn}\ K_{xyn}\right]$$

$$K_Y = \text{diag}\left[K_{yxp}\ K_{yyp}\ K_{yxn}\ K_{yyn}\right]$$

The equivalent state space force equations which suitable for proposed sliding mode observer is given by:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{y}_1 \\ \dot{y}_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -\frac{k}{m} & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -\frac{k}{m}-g & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ y_1 \\ y_2 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ K_{xxp} & K_{xyp} & K_{xxn} & K_{xyn} \\ 0 & 0 & 0 & 0 \\ K_{yxp} & K_{yyp} & K_{yxn} & K_{yyn} \end{bmatrix} \times \begin{bmatrix} i_{xp}^2 \\ i_{yp}^2 \\ i_{xn}^2 \\ i_{xn}^2 \end{bmatrix} \qquad (5)$$

The modeling of BSRM dynamics for motoring purpose:

$$\frac{d\psi}{dt} = -rN(\theta)\psi+V+w_\psi \qquad (6)$$

$$\frac{dw}{dt} = \frac{T_e - T_l}{J} - \frac{B}{J}w+\frac{T_e}{J}+w_w \qquad (7)$$

$$\frac{d\theta}{dt} = w+w_\theta \qquad (8)$$

$$i = N(\theta)\psi \tag{9}$$

$$T_e = T_e(i, \theta) \tag{10}$$

Proposed Sliding Mode Observer (SMO) for BSRM rotor displacements: A variety of conditions is considered for modeling of SMO to estimate the position and rotor displacement in x-y directions. The indirect estimation of position and displacements are modeled from voltages and currents of individual phases. An error correction term is implemented based on the difference between the currents of the mathematical model and measured model values. The estimation of currents for each phase will give integral errors when the motor is operated at low and zero speeds. It is very important to demonstrate the SMO at low and zero speeds. However, operating at low and zerospeeds will bound the accumulated errors because of the current and the flux of each phase will periodically goes to zero (Fig. 2):

$$S = \hat{i} - i = \begin{bmatrix} N_0 & 0 & M_0 \end{bmatrix} \begin{bmatrix} \hat{\psi} - \psi & \hat{w} - w & \hat{\theta} - \theta \end{bmatrix}^T \tag{11}$$

$$S = N_0 e_\psi + M_0 e_\theta;\ \dot{S} = N_0\, \dot{e}_\psi + M_0\, \dot{e}_\theta\, \dot{S} = N_0\, \dot{e}_\psi + M_0\, \dot{e}_\theta;\ S^T\, \dot{S} \le 0 \tag{12}$$

$$\dot{\hat{X}}_2 = \frac{k}{m} x_1 + K_x I_x + K_y I_y + K_{x2} \operatorname{sign}(\hat{I}_x - I_x) \tag{13}$$

$$\dot{\hat{Y}}_2 = \frac{k}{m} y_1 + K_y I_y + K_x I_x + K_{y2} \operatorname{sign}(\hat{I}_y - I_y) \tag{14}$$

The selection of suspending force poles are listed in Table 1. There are three modes of asymmetric converter operations, those are magnetization, freewheeling and demagnetization modes. These three are selected depends upon the state of inputs to an asymmetric converter. The multi-switch inputs 1, 0, -1 which are signals came from of current hysteresis controller. When switching state one refers to magnetization mode, 0 corresponding to freewheeling mode and -1 refers to demagnetization mode. If the current hysteresis controller output is 1, i.e., magnetization mode operation, the multi-switch will connects and excites the suspending force windings I_{s1} and I_{s2} when $F_x{}^*>0$, $F_y{}^*>0$ through the asymmetric convertser.

Table 1: Selection of suspension poles on stator

Desired force	Suspending force poles selection
If $F_x \ge 0$, $F_y \ge 0$	I_{s1} and I_{s2}
If $F_x \ge 0$, $F_y \le 0$	I_{s1} and I_{s4}
If $F_x \le 0$, $F_y \le 0$	I_{s3} and I_{s4}
If $F_x \le 0$, $F_y \ge 0$	I_{s3} and I_{s2}

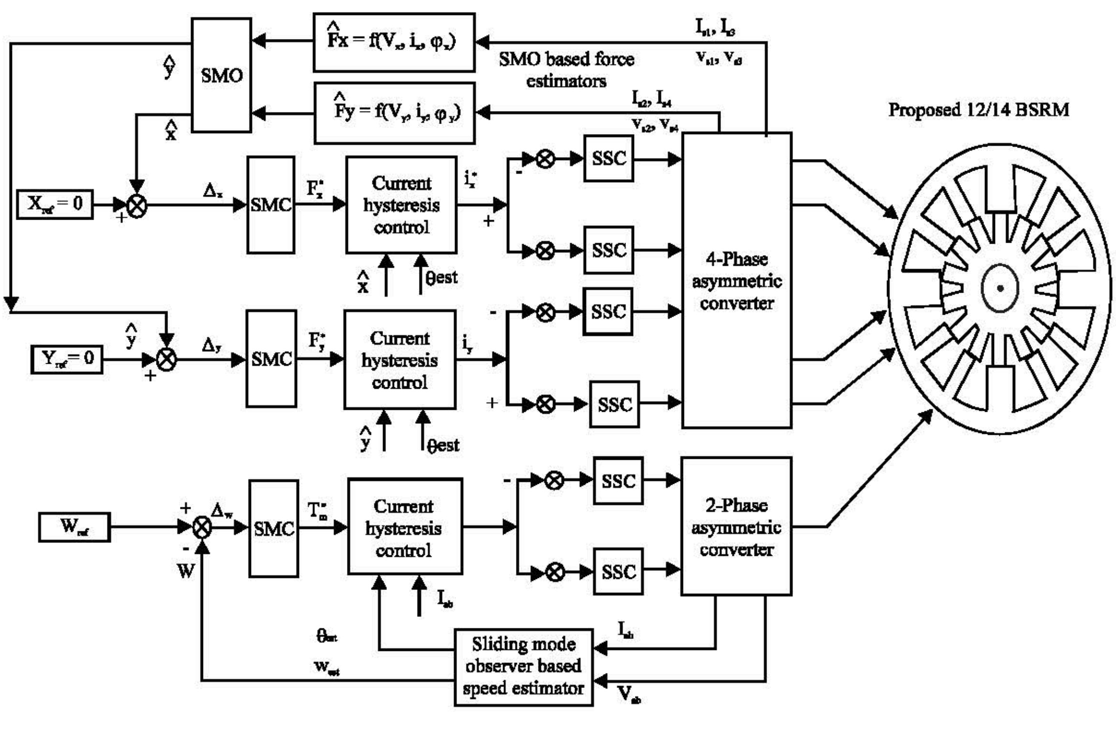

Fig. 2: Proposed sliding mode observer and control block diagram of BSRM

RESULTS AND DISCUSSION

In order to give the better explanation about the previous the oretical analytical studys 2.1 and 2.2 and to verify its soundness, equivalent simulations on a 12/14 BSRM are done with MATLAB/Simulink and Infolytica/Magnet 2D Software from Fig. 3. The suspension force is function of levitation current and rotor position.

Estimation of BSRM parameters at healthy condition: Figure 4 shows the estimated rotor position, rotor displacements, suspension forces, voltages and currents of sliding mode observer when a BSRM drive is subjected to initial reference displacements of -100 and -60 at 0 sec. The observer results indicates that the estimated rotor displacements and rotor positions can track the actual values, even under different large reference errors. The sliding mode observer begins to researcher for estimation of position and speed and displacement after 150 µsec. When the BSRM drive is started up with the arbitrary initial rotor position from Fig. 4, it can be observed that the proposed observer can rapidly track the rotor displacement is <0.0001 sec, rotor position is <0.0011 sec and the motor speed is <0.01 sec, the corresponding voltage and phase currents are also shown in Fig. 4.

Estimation of BSRM parameters when suspension loads applied and the moment of inertia doubled: Figure 5 illustrates the estimated BSRM parameters by using SMO when the motor under suspension load disturbances

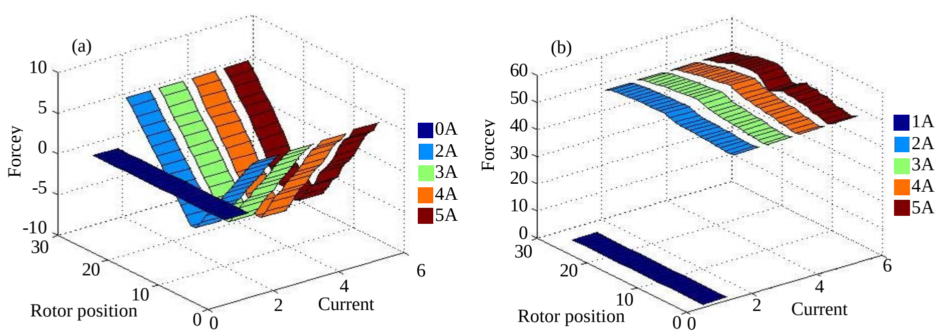

Fig. 3: a) X-directional suspension force w.r.t current and rotor position and b) Y-directional suspension force w.r.t. current and rotor position

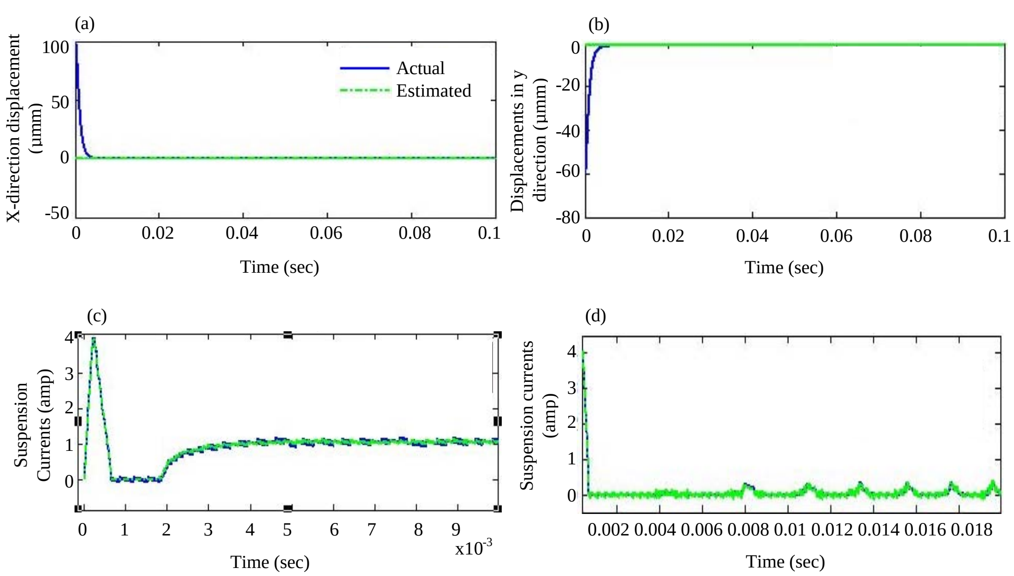

Fig. 4: Continue

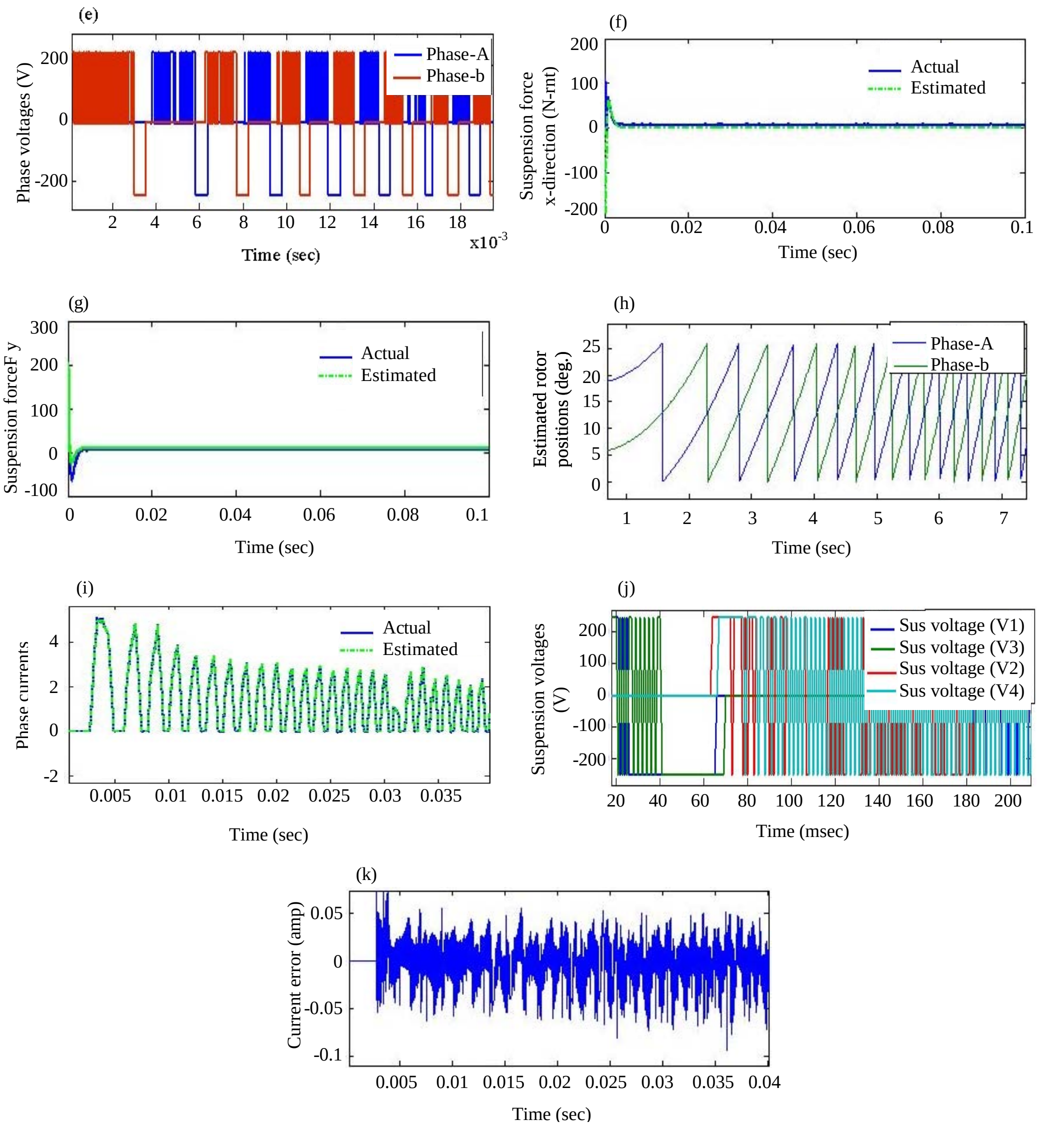

Fig. 4: a) Rotor X-actual and estimated displacements; b) Rotor Y-actual and estimated; c) Suspension currents in X-directional; d) Suspension currents in Y-directional; e) Actual suspension voltages; f) X-axis suspension forces; g) Y-axis suspension forces; h) Estimated rotor positions; i) Main phase-A currents; j) Main phase controlled voltages and k) Current error of phase-A

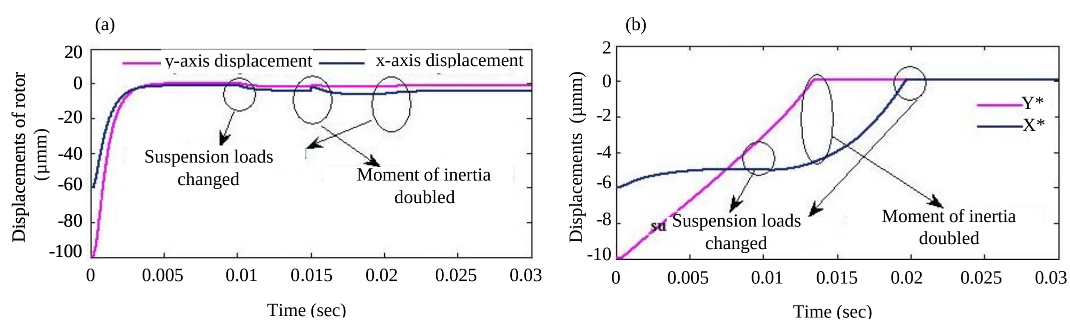

Fig. 5: Continue

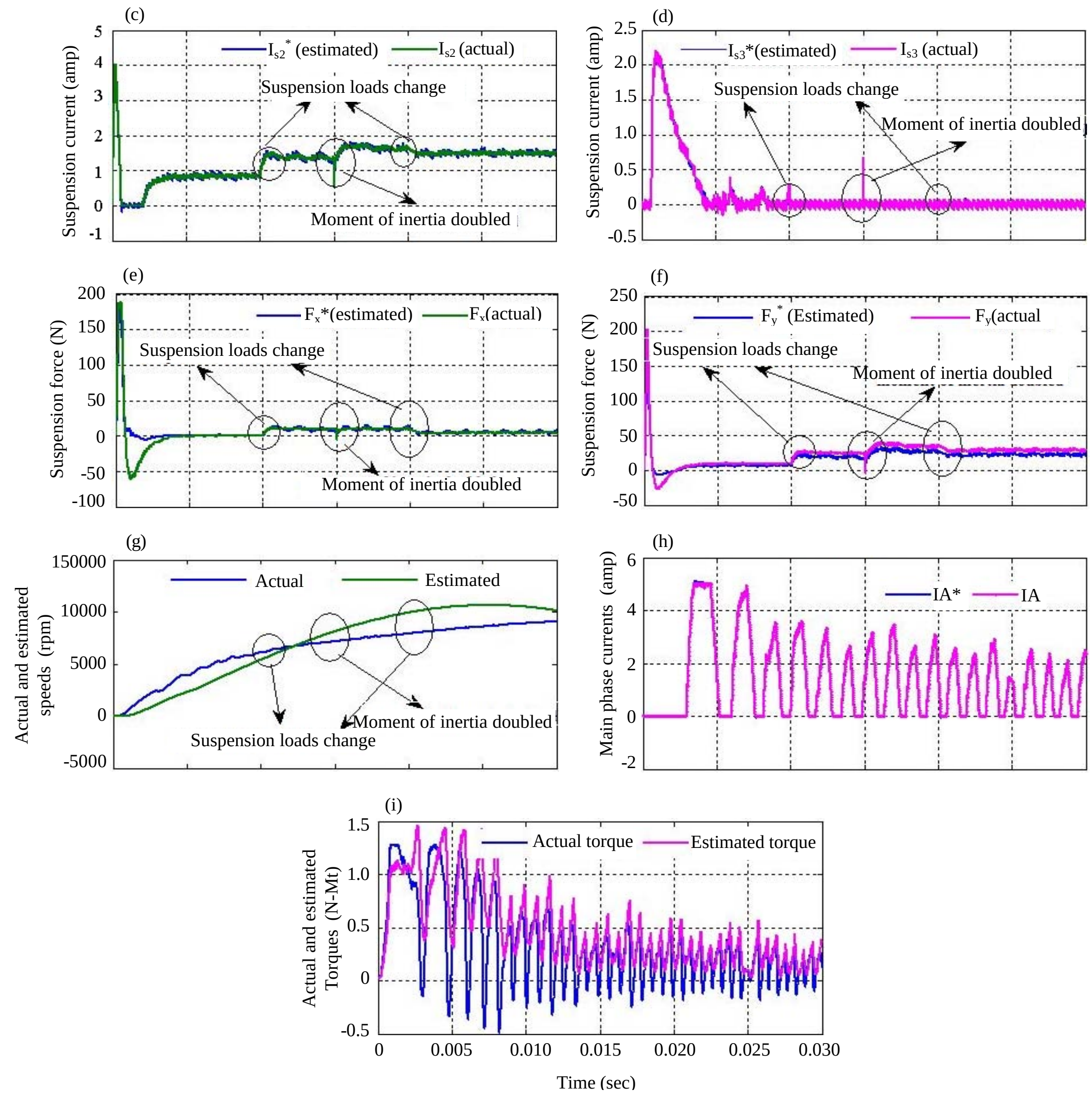

Fig. 5: a) Actual rotor displacements when loads applied; b) Estimated rotor displacements when loads applied; c) X-axis suspension currents when loads applied; d) Y-axis suspension currents when loads applied; e) X-axis suspension forces when loads applied; f) Y-axis suspension forces when loads applied; g) Actual and estimated speeds when loads applied; h) Main phase-A currents when loads applied and i) Acyual and estimated torques when loads applied

which are applied abruptly at 0.01 and 0.02 sec. The moment of inertia is doubled suddenly at 0.015 sec. At the instant of change of loads and moment of inertia, there is a temporary increment of errors of rotor displacements, suspension forces and currents of proposed SMO for BSRM.

From the above results, the proposed SMO for BSRM provides the stable and accurate position estimation, rotor displacement estimation and speed estimation even though there is a sudden change in reference and suspension loading conditions. The whole system reached its expected precision tracking and also shows the robustness and insensitivity responses to all rotor disturbances.

CONCLUSION

In this study, the accurate estimation of rotor displacements and rotor positions of BSRM were done by using indirect sensor less Sliding Mode Observer (SMO). The robustness and the fast convergence of SMO was tested at different initial reference displacements and different suspension load forces. At the instant of change of loads there is a temporary increment of errors of position and rotor displacements of proposed SMO for BSRM. The whole system reached its expected precision tracking in less time. The fast convergence rate and more robustness and disturbance rejection capability properties were carefully analyzed. The sliding mode observer offered more stable and accurate rotor displacement, position and speed estimations under any unexpected changes of reference and suspension loading conditions.

NOMENCLATURE

m	=	Mass (kg)
g	=	Gravitational Force in y direction
F_x and F_y	=	Suspension forces in x and y axis, respectively
K_x and K_y	=	Suspension force equivalent constant matrices in x and y axis, respectively
K_{xxp}, K_{yyp} K_{xyp}, K_{yxp} and K_{xxn}, K_{yyn}, K_{xyn} and K_{yxn}	=	Equivalent suspension force constants in x, y and positive in both negative directions, respectively
I_x and I_y	=	Suspension current matrices in x and y-axis, respectively
i_{xp},i_{yp},i_{xn},i_{yn}	=	Individual suspension currents in x and y axis in both positive and negative directions, respectively
ψ	=	Per phase flux linkages
r	=	Per phase resistance
N	=	Phase reversal inductances
θ	=	Rotor position per phase
V	=	Phase voltage (V)
W	=	Rotor speed (rpm)
T_e and T_l	=	Net electromagnetic Torque produced and load Torque applied
J and B	=	Combined moment of Inertia of the rotor and its damping coefficient
i	=	Per phase current (amp)
S	=	Switching manifold
N_0, M_0	=	Error coefficient constants for design of switching surface
e	=	Error between actual and measured values

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